NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

TOTAL LIFE CYCLE MANAGEMENT – ASSESSMENT TOOL:
AN EXPLORATORY ANALYSIS

by

Brad Young

June 2008

Thesis Advisor:	Thomas W. Lucas
Second Reader:	Sergio Posadas

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** June 2008	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. Title and Subtitle Total Life Cycle Management – Assessment Tool: An Exploratory Analysis			**5. FUNDING NUMBERS**
6. Author(s) Brad Young			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) Marine Corps Installations and Logistics Command			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

It is essential for the Marine Corps to ensure the successful supply, movement and maintenance of an armed force in peacetime and combat. Integral to an effective, long-term logistics plan is the ability to accurately forecast future requirements to sustain materiel readiness. Total Life Cycle Management – Assessment Tool (TLCM-AT) is a simulation tool combining operations, maintenance, and logistics. This exploratory analysis gives insight into the factors used by TLCM-AT beyond the tool's embedded analytical utilities. A Java program is developed to automate multiple changes to TLCM-AT's database, execute simulation runs and record output data. A scenario deploying LAV-25 vehicles to a tropical region, with three courses of action, provides the basis for analysis. The research provides a description of the analysis available by TLCM-AT as a stand-alone tool, and concludes with how design of experiments (DOE) expands insights gained. This thesis provides a framework for using DOE with TLCM-AT, identifies a structured use of TLCM-AT for decision makers, and provides enhancements that enable more effective use of TLCM-AT. Results indicate no practical change in operational availability (Ao) when varying five factors, using 129 design points and 15,480 replications. The factors adjusted are: spares, depot capacity, induction quantity, part repair time and part degradation time. Results also reveal synergies between the modeled factors and numbers of spares to be the dominant factor Ao.

14. SUBJECT TERMS Life Cycle Management, Life-Cycle Costs, Operational Availability, Data Farming, Design of Experiments, Nearly Orthogonal Latin Hypercube, Marine Corps Installation and Logistics, TLCM-AT, Light Armored Vehicle, Marine Corps Logistics Command, Clockwork Solutions, SEED Center			**15. NUMBER OF PAGES** 69
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

TOTAL LIFE CYCLE MANAGEMENT – ASSESSMENT TOOL: AN EXPLORATORY ANALYSIS

Brad Young
Major, United States Marine Corps
B.S., Texas A&M University, 1993

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
June 2008

Author: Brad Young

Approved by: Thomas W. Lucas
Thesis Advisor

Sergio Posadas
Second Reader

James N. Eagle
Chairman, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

It is essential for the Marine Corps to ensure the successful supply, movement and maintenance of an armed force in peacetime and combat. Integral to an effective, long-term logistics plan is the ability to accurately forecast future requirements to sustain materiel readiness. Total Life Cycle Management – Assessment Tool (TLCM-AT) is a simulation tool combining operations, maintenance, and logistics. This exploratory analysis gives insight into the factors used by TLCM-AT beyond the tool's embedded analytical utilities. A Java program is developed to automate multiple changes to TLCM-AT's database, execute simulation runs and record output data. A scenario deploying LAV-25 vehicles to a tropical region, with three courses of action, provides the basis for analysis. The research provides a description of the analysis available by TLCM-AT as a stand-alone tool, and concludes with how design of experiments (DOE) expands insights gained. This thesis provides a framework for using DOE with TLCM-AT, identifies a structured use of TLCM-AT for decision makers, and provides enhancements that enable more effective use of TLCM-AT. Results indicate no practical change in operational availability (Ao) when varying five factors, using 129 design points and 15,480 replications. The factors adjusted are: spares, depot capacity, induction quantity, part repair time and part degradation time. Results also reveal synergies between the modeled factors and numbers of spares to be the dominant factor Ao.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF SYMBOLS, ACRONYMS, AND/OR ABBREVIATIONS

AAV	Amphibious Assault Vehicle
Ao	Operational Availability
AWM	Awaiting Maintenance
AWP	Awaiting Parts
CASC	Capability Assessment Support Center
COA	Course of Action
DOE	Design of Experiments
DOF	Depot Overhaul Factor
ECP	Engineering Change Program
EEAP	Enhanced Equipment Allowance Pool
ENSIP	Engine Structural Integrity Program
FI	Fault Isolation
FY	Fiscal Year
GUI	Graphical User Interface
IROAN	Inspect and Repair Only As Necessary
JLTV	Joint Light Tactical Vehicle
LAV	Light Armored Vehicle
LCMI	Life Cycle Modeling Integrator
LOGCOM	Marine Corps Logistics Command
LRU	Line Replacement Unit
LRT	Logistics Response Time
LTI	Limited Technical Inspection
LW155	Lightweight 155mm Howitzer
MAC	Maintenance Allocation Chart
MEF	Marine Expeditionary Force
MOE	Measure of Effectiveness
MPS	Maritime Prepositioning Force
MTVR	Medium Tactical Vehicle Replacement
MWS	Master Work Schedule
NOLH	Nearly Orthogonal Latin Hypercube
NPS	Naval Postgraduate School
NRTS	Not Repairable This Station
O&S	Operation and Sustainment
OEM	Original Equipment Manufacturer
O-level	Operational Level
PBL	Performance-Based Logistics
PEI	Principle End Item
PM	Program Manager
SEED	Simulation Experiments and Efficient Designs
SOE	System Operational Effectiveness
SRAN	Stock Record Account Number
R&D	Research and Development

RCT	Repair Cycle Time
TLCM	Total Life Cycle Management
TLCM-AT	Total Life Cycle Management Assessment Tool
T/O	Table of Organization
ULSS	User's Logistics Support Summary
USMC	United States Marine Corps

ACKNOWLEDGMENTS

I have stepped out upon this platform that I may see you and that you may see me, and in the arrangement I have the best of the bargain.

Abraham Lincoln, 16 February 1861

First and foremost, I would like to thank my Lord and Savior Jesus Christ. Through Him all things are possible. Secondly, I would like to thank the United States Marine Corps for giving me the opportunity to expand my mind while serving with the finest fighting force the world has ever known. I also owe a debt of gratitude to my teachers and mentors at Texas A&M University. The Spirit of Aggieland remains with me, and gives me a foundation of strength and moral courage to accomplish anything in life. Gig'em Ags!

The completion of this thesis would not have been possible without the help and guidance of the following individuals at the Naval Postgraduate School:

Professor Thomas Lucas, Thesis Advisor

Lieutenant Colonel Sergio Posadas, USMC, Thesis Second Reader

Colonel Ed Lesnowicz, USMC (Ret.), Thesis Consultant

Lieutenant Alberto Garcia, USN, Thesis Partner and Friend

I am most grateful to my family. With their support and guidance I have been able to stay the course throughout my life and career. Finally, I want to thank my brilliant daughter, Sydney Jordan Young. Without her beautiful smile to remind me of life's true importance, none of this work would have been possible. Thank you, Sweetie.

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

Logistics is a vital part of the Marine Corps' vision of developing a force capable of performing and successfully completing the missions of the twenty-first century. It is essential that the Marine Corps ensures the successful supply, movement and maintenance of an armed force in peacetime and combat.

This thesis centers on the Total Life Cycle Management – Assessment Tool (TLCM-AT). Total Life Cycle Management (TLCM) defines the design, engineering, manufacturing, disassembly and disposal of a system. Decision makers who use TLCM must understand its impact on combat effectiveness and on the development of systems required for success in modern warfare. The Marines acquired TLCM-AT to improve upon their ability to manage TLCM and maintain a more reliable fighting force. This summary provides a functional overview of TLCM-AT, the research methodology, conclusions and recommendations. The analysis is designed to explore the capabilities of TLCM-AT with multiple quantitative techniques, in order to develop an analytical process that enables tactical users to more readily employ TLCM-AT.

TLCM-AT is a simulation tool developed by Clockwork Solutions in Austin, Texas. It is a holistic, continuous-loop representation of the life cycle of a weapon system: combining operations, maintenance, and logistics. TLCM-AT's model structure and organization enables the Marine Corps to model the myriad of industry-accepted elements that directly affect the life cycle of a system. TLCM-AT assists weapons systems managers with evaluating, quantifying, and reducing life-cycle costs without adversely impacting fleet readiness and availability. Users can run "what if" scenarios by manipulating data inputs to examine the long-term effects to life-cycle policy decisions. Scenarios are adjusted by the user via the scenario editor in TLCM-AT's graphical user interface (GUI). This research extends the normal analysis by implementing the concepts of data farming and design of experiments (DOE) as employed by the Simulation Experiments and Efficient Designs (SEED) Center at the Naval Postgraduate School (NPS).

This thesis provides the following:

- A framework for using DOE with TLCM-AT.
- A structured use of TLCM-AT for USMC decision makers.
- Enhancements that enable more effective usage of TLCM-AT.

A notional scenario deploying Light Armored Vehicles (LAVs) to a tropical environment serves as the background for this prototype analysis. According to the scenario, the Marine Corps seeks to deploy one LAV-25 battalion, and eventually a follow-on battalion for contingency operations in a hot, humid environment. Maintenance personnel anticipate numerous unscheduled removal events of two computerized parts that historically perform poorly in humid conditions. Three potential courses of action (COAs) are suggested to help mitigate the anticipated problem.

COA 1: Send a large number of spares with the follow-on battalion.

COA 2: Invest in improved Line Replacement Units (LRU). The research and development (R&D) cost for the one-month R&D program is $1M, and the new LRUs cost an additional 1.5 times the cost of the old type. Bring a lesser number of the improved spares and install them whenever the old type is removed. When the old type is condemned (removed from maintenance system), buy the new type.

COA 3: A variant of COA 2, except that the old type is purchased whenever the LRUs are condemned. No money is invested in the new LRUs. The idea is to save some money, while accomplishing the same goals.

Each scenario is modeled separately in TLCM-AT's Microsoft Access database. Five factors are chosen to explore over the COAs using Nearly Orthogonal Latin Hypercube (NOLH) experimental designs. A Java program is created to automatically run each scenario using 129 input combinations. The five factors varied in this study are:

- **Spare levels:** The total number of spares at each repair location.
- **Induction Quantity:** A limit on the number of inductions (number of items a maintenance facility can accept) that can occur in the given quarter and year at a single repair facility.
- **Capacity:** The number of parts that can be processed concurrently at a single repair facility.

- **Service Times:** The time it takes to repair a part.
- **Unscheduled Removal Rates:** The part failure rate.

The NOLH allows for systematic variation of the factors to broadly explore their effect on the measure of effectiveness (MOE). Ao is chosen as the MOE for this study. Upon completion of the Java program, a comma-separated file is created containing Ao by quarter over a 20-quarter period.

First, each scenario is run once with 100 replications. This type of simulation typifies the kind of study a common user of TLCM-AT would use to produce a quick-turn analysis of a specific scenario. Results show COA-2 saves $3.2M compared to COA-1 and $15.8M compared to COA-3. COA-2 had lower overall operation and sustainment (O&S) costs for spares replenishment and produced the least impact on repair facilities by producing a lower number of maintenance tasks performed. Furthermore, each scenario maintained relatively equal Ao throughout the contingency and for the full 20-quarter period. All scenarios produced a much higher Ao than the baseline, thus maintaining the status quo.

DOE implementation with TLCM-AT across all scenarios and 129 design points each produced similar results in regard to Ao. Statistically significant differences in Ao are observed after quarter 12 (the end of contingency operations). However, these differences are not practically significant, as Ao varied no more than 4% for each scenario.

Regression analysis produced relatively low R^2 values, representing a low amount of variance explained in the model by the five factors. In cases where R^2 is low, the results show that other factors (besides those used in this study) should be considered. Thirty-two stepwise regressions are conducted, and R^2 increases in all cases as interaction terms are added to the models. This result shows that including main effects alone did not capture the complete picture. Significant factors for scenario two are determined to be spares, spares × spares, spares × service time and induction quantity × degradation time. The significance of interaction terms reveals synergies between the factors.

Paired two-sample t-Tests between each scenario are completed to determine whether or not two population means of Ao are equal. In each test, the hypothesized mean difference is zero. Low p-values are produced for all six comparisons, revealing a statistically significant difference in mean Ao between each scenario. However, the mean difference is not practically significant because the variation in mean Ao is small. For example, going from 81.8% to 82.1% Ao is not significant enough to make practical impacts on the overall operational picture over a range of inputs. However, there are some differences in other measures such as cost and maintenance utilization.

In conclusion, exploitation of TLCM-AT is accomplished through development of a Java program to automate implementation of DOE and NOLH with TLCM-AT. The simulated scenarios used in this analysis form a strong foundation for further TLCM-AT studies that use DOE to analyze life cycles. Java code written to extract many different MOEs gives insight to the factors most affecting outcomes of simulation runs. This analysis adds depth to typical “what if” scenario runs, and informs decision makers on the consequences of decisions regarding Marine Corps weapon systems. It is recommended that research continue into embedding TLCM-AT in a data farming environment. Furthermore, it is recommended that a prototype study be performed.

I. INTRODUCTION

> *Develop better readiness and sustainment indicators based on predictive modeling, so that timely changes to strategies, plans, and programs can be implemented.*
>
> *Commandant's Planning Guidance, November 2006*

A. BACKGROUND AND MOTIVATION

The United States Marine Corps (USMC) continually works to shape logistics plans and policies to sustain excellence in combat effectiveness. Logistics is an extremely vital part of the Marine Corps' vision of developing a force capable of performing and successfully completing the missions of the twenty-first century. It is essential that the Marine Corps ensures the successful supply, movement and maintenance of an armed force, both in peacetime and in combat. Integral to an effective, long-term, logistics plan is the ability to accurately forecast future requirements to sustain materiel readiness as well as determine future force structural needs. This study focuses on the elements that affect the life cycle of weapons systems, such as level of spares, depot capacity and repair times.

Enterprise-level Total Life Cycle Management (TLCM) is the formal process to identify, analyze, and implement synergistic "cradle-to-grave" solutions that optimize the acquisition and logistics chain across the Marine Corps. The following items impact the entire Marine Corps and require an enterprise view[1]:

- Automatic Logistics/Prognostics
- Performance-Based Logistics
- Design-in Reliability, Maintainability and Supportability
- Direct Vendor Delivery
- Logistics Footprint
- Fuel Efficiency

[1] Marine Corps Order 4000.57, Enclosure (1), Commandant of the Marine Corps, Subject: Marine Corps Life Cycle Management, 16 September 2005, p. 1.

- Depot Maintenance
- Condition-Based Maintenance Technology
- Logistics Operational Architecture
- Automated Identification Technology

TLCM defines the design, engineering, manufacturing, disassembly and disposal of a system. TLCM includes the set of decisions and actions that determine the performance and availability of a weapons system in the context of its environment. Therefore, decision makers must use TLCM and understand its impact on combat effectiveness and on the development and cost of weapons systems needed for success in modern warfare.

The Marine Corps has invested in Clockwork Solutions (www.clockwork-solutions.com) to adapt a discrete event simulation tool for use in conducting TLCM. Clockwork Solutions is a provider of reliability-centered total life cycle performance prediction tools. One of their simulation tools, the TLCM Assessment Tool (AT), is an emerging enhancement module to the Life Cycle Modeling Integrator (LCMI). LCMI is a Web-based set of decision support modules that integrates historical data and converts it to quality logistics intelligence for the USMC. Within the TLCM-AT module is the Fault Isolation (FI) model, which uses a multivariate, dimension reduction algorithm to create a ranked index of the components of a principal end item (PEI). Program Managers (PMs) can use this decision support tool to enhance the effectiveness of their depot maintenance rotation programs. The FI model can also help identify components to be inspected during Inspect and Repair Only As Necessary (IROAN) programs.

The aging of such systems as the Amphibious Assault Vehicle (AAV) and the Light Armored Vehicle (LAV) creates a greater level of uncertainty about their Ao. Simulation tools, such as TLCM-AT, are helpful in identifying critical factors that affect the Ao of weapon systems. Simulation can make forecasting more accurate and enable decision makers to be proactive with TLCM. An exploratory analysis on model factors pinpoints factors with the strongest effects on output such as system reliability, Ao and cost. Furthermore, sensitivity analysis of critical factors better defines thresholds for decision makers. This thesis examines the capabilities of TLCM-AT.

B. RESEARCH QUESTIONS

The exploratory analysis gives insight into the factors used by TLCM-AT. While this analysis is not exhaustive, the following questions guide this research:

- Which factors modeled in the TLCM-AT have a critical effect on the Ao of the LAV-25?
- How should data farming be applied to the TLCM-AT model?
- How sensitive are the factors (spares, capacity, induction, service time, degradation time) to defining thresholds for decision makers?

C. SCOPE OF THESIS

This analysis examines the capabilities of the TLCM-AT. The goal is to use multiple quantitative analysis techniques in order to develop a methodology to enable tactical users to more readily employ the TLCM-AT tool.

D. METHODOLOGY

This thesis uses the TLCM-AT, for which three scenarios are created, each revolving around a potential decision about the LAV-25. Each scenario represents a possible course of action (COA) for the decision maker. In each scenario, five factors are adjusted:

- **Spare levels:** The total number of spares at each repair location.
- **Induction Quantity:** A limit on the number of inductions that can occur in the given quarter and year at a single repair facility.
- **Capacity:** The number of parts that can be processed concurrently at a single repair facility.
- **Service Times:** The time it takes to repair a part.
- **Unscheduled Removal Rates:** The part failure rate.

This study determines the effect these factors have on the Ao of the LAV-25. Ao is defined as the number of operational platforms divided by the total number of platforms at a given base or bases at a given future time interval. Each scenario is explained in detail in Chapter III.

The scenarios are developed based on a range of inputs of the factors listed above. The factors are used to create several design points developed using the Nearly Orthogonal Latin Hypercube (NOLH).[2] Scenario runs are replicated in the simulation and then analyzed. The analysis uses data farming, as employed by the Simulation Experiments and Efficient Designs (SEED) Center at the Naval Postgraduate School (NPS) and the International Data Farming Workshop. Data farming uses high-speed computing to run simulations thousands of times while simultaneously varying many input factors. Using experimental designs developed at NPS, the data farming results is analyzed. The statistical analysis reveals the strengths, weaknesses and sensitivities of the model. The result is a preliminary study of support, based on analysis, to aid future users of TLCM-AT.

E. BENEFITS OF THE STUDY

This study provides the Marine Corps with analytical support for TLCM-AT. Data farming and NOLH provide a unique approach for the study by allowing the identified factors to be widely varied, and for multiple simulation runs to be accomplished for post-run analysis. Chapter II provides a brief description of discrete event simulation modeling followed by a functional overview of TLCM-AT. Chapter III explains specifically how data farming and NOLH are used in the simulation runs. Chapter IV contains data analysis from the resulting data obtained from multiple simulation runs. Chapter V provides conclusions and identifies future areas of study. Currently, the Marine Corps does not know all the capabilities and limitations of TLCM-AT. The aim of this study is to provide those insights into how TLCM-AT can be used to help decision makers make more informed decisions regarding TLCM.

[2] NOLH concept developed by Lieutenant Colonel Thomas M. Cioppa, United States Army. Detailed description found in his dissertation, "Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models," Ph.D. in Operations Research, Naval Postgraduate School, Monterey, California, September 2002.

II. MODEL BACKGROUND AND CAPABILITIES

A. INTRODUCTION

Before conducting an exploratory analysis, one must understand the intricacies of the model itself. The purpose of this chapter is to introduce the reader to TLCM-AT. It begins with a brief description of mathematical models, both deterministic and stochastic. This discussion leads into a functional overview of TLCM-AT, including criteria, structure and applications.

B. DISCRETE EVENT STOCHASTIC MODELING

Mathematical models can be categorized broadly as probabilistic or deterministic. A deterministic model uses factors and variables without random fluctuations. The system is entirely defined by the initial conditions. A deterministic model provides a single point estimate which serves as a “best guess” for an unknown population parameter. A stochastic model considers randomness in one or more of its factors or variables. By allowing random variation in one or more inputs over time, a stochastic model estimates probability distributions of potential outcomes. What results is not a single point estimate but a distribution of possible outcomes.

After empirical data is collected, a theoretical probability distribution is often fit to the data to attain a more general description of the underlying process. The population parameters can be approximated for the distribution. Stochastic processes provide a better understanding of inherently stochastic real-life situations.

The TLCM-AT is a discrete event stochastic model. The aim of TLCM-AT is the integration of discrete event performance models into the USMC decision support enterprise. Clockwork Solutions has modeled five USMC systems:

- Light Armored Vehicle (LAV-25)
- Medium Tactical Vehicle Replacement (MTVR)
- Lightweight 155mm Howitzer (LW155)
- Joint Light Tactical Vehicle (JLTV)
- Amphibious Assault Vehicle (AAV)

These five systems are chosen based on the following criteria:

- Maintenance Cost
- Operational Usage
- High and Low Readiness
- Sample Size (High and Low Density Table of Authorized Material Control Number [TAMCN])
- Old System
- New System
- Recent Mission Change
- Configuration Change

C. TLCM-AT FUNCTIONAL OVERVIEW

TLCM-AT is a technology developed to assist weapon systems fleet managers with evaluating, quantifying and reducing life-cycle costs without adversely impacting fleet readiness and availability.[3] This model is a holistic, continuous-loop representation of the life cycle of any weapons system: it combines operations, maintenance, and logistics, as shown in Figure 1. The inner loop contains examples of the inputs to TLCM-AT, and the items on the outside of the loop represent examples of outputs obtained after simulation runs.

[3] Clockwork Solutions, Inc., "Predictive Modeling Technology and Consulting Services in Support of Phase III TLCSM," Final Project Report (1992-2005), submitted to Headquarters, Marine Corps Installations and Logistics, 31 December 2007, p. 1.

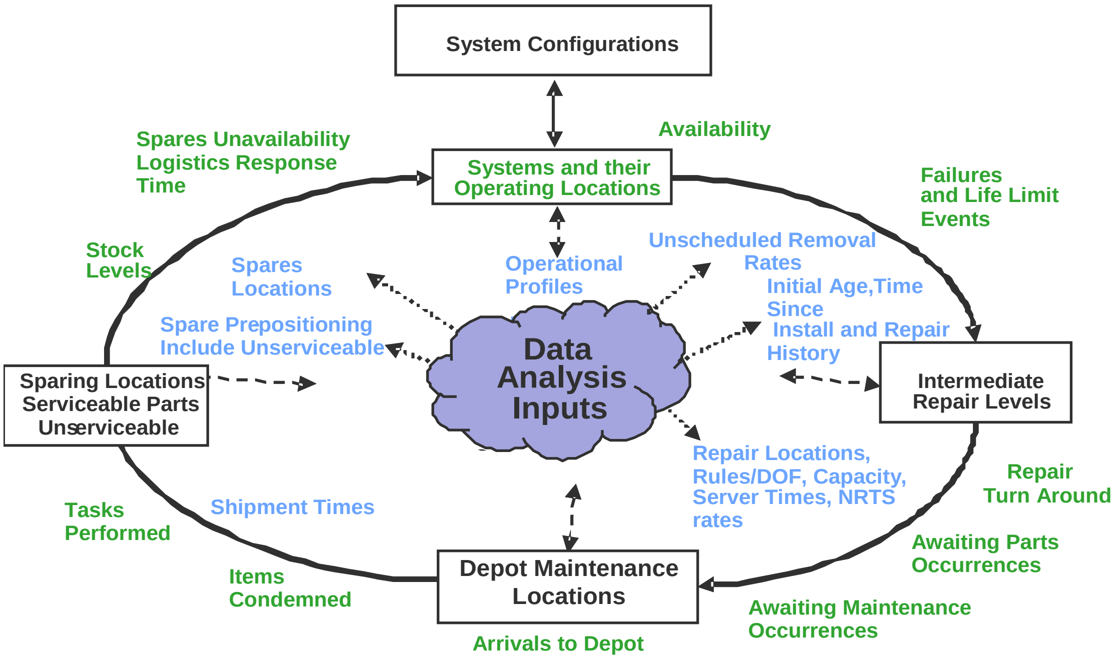

Figure 1. TLCM-AT continuous-loop model (After)[4]

An individual weapons system TLCM-AT model is composed of six interactive components[5]:

- **Initialization:** Readiness condition and location of systems and parts at simulation start.
- **System Model:** Work breakdown structure of the system and its variants.
- **Operations Model:** Current and future operations according to base location, platform type, or serialized system.
- **Maintenance Model:** Actions on a component in maintenance as described by capacity constraints.
- **Sustainment Model:** Spares, lateral resupply, depot upgrades, and induction programs.
- **Cost Model:** Cost of purchases and activities, including maintenance, training, initial and subsequent provisioning of parts, storage, shipping, and upgrades.

[4] Clockwork Solutions, Inc., "TLCM-AT Training Material," Chapter 2, Naaman Gurvitz, Ph.D. 7 August 2007, p. 2.

[5] Clockwork Solutions, Inc., *Technical Reference Manual*, "Aircraft Total Life Cycle Assessment Software Tool (ATLAST)," Version 5.0., (1992-2005), Austin, Texas, p. 14.

The system model consists of input data that represents the structure, location, age and status of components (installed, spares, serviceable/unserviceable). The System Operational Effectiveness (SOE) parts usage database is used to build the system structure for the AAV, LAV, and MTVR models. SOE is a tool developed by Marine Corps Systems Command to monitor and measure system operational effectiveness attributes on a wide range of Marine Corps ground weapons systems. It automatically calculates and summarizes key reliability, maintainability and availability metrics. SOE provided part usage data as well as failure rates. The rest of the models are built from a variety of sources: spreadsheets from Marine Corps Logistics Command (LOGCOM), the Capability Assessment Support Center (CASC), and queries to the program manager's office for the individual weapon systems. The LW-155 model does not use SOE at all; it starts with original equipment manufacturer (OEM) structure and reliability information. Lastly, the JLTV model is built by extracting relevant subsystems from a high-fidelity LAV model with an indentured system structure. Failure rates for the JLTV components are exponentially distributed and in accordance with historical LAV maintenance records. For an exhaustive list and explanation of TLCM-AT's inputs and outputs, refer to the technical manual, which can be provided by Clockwork Solutions.

The operations module consists of the base structure and placement of systems and the current and future usage rates. Figure 2 shows a mapping of the base structure and system placement for the LAV variants. The MTVR model has a total of 7,597 vehicles distributed between I-IV Marine Expeditionary Force (MEF), 7 MEF, Maritime Prepositioning Ships (MPS) and Depot inventory. The JLTV model uses eight notional bases and will gradually field 900 systems among them from 2009-2012. The LW-155 model places the Marine artillery regiments at the Operational Level (O-level), in addition to the Enhanced Equipment Allowance Pool (EEAP), the Army's field artillery school at Fort Sill, and the Aberdeen Proving Grounds. Guns are fielded according to the schedule in the User's Logistics Support Summary (ULSS).

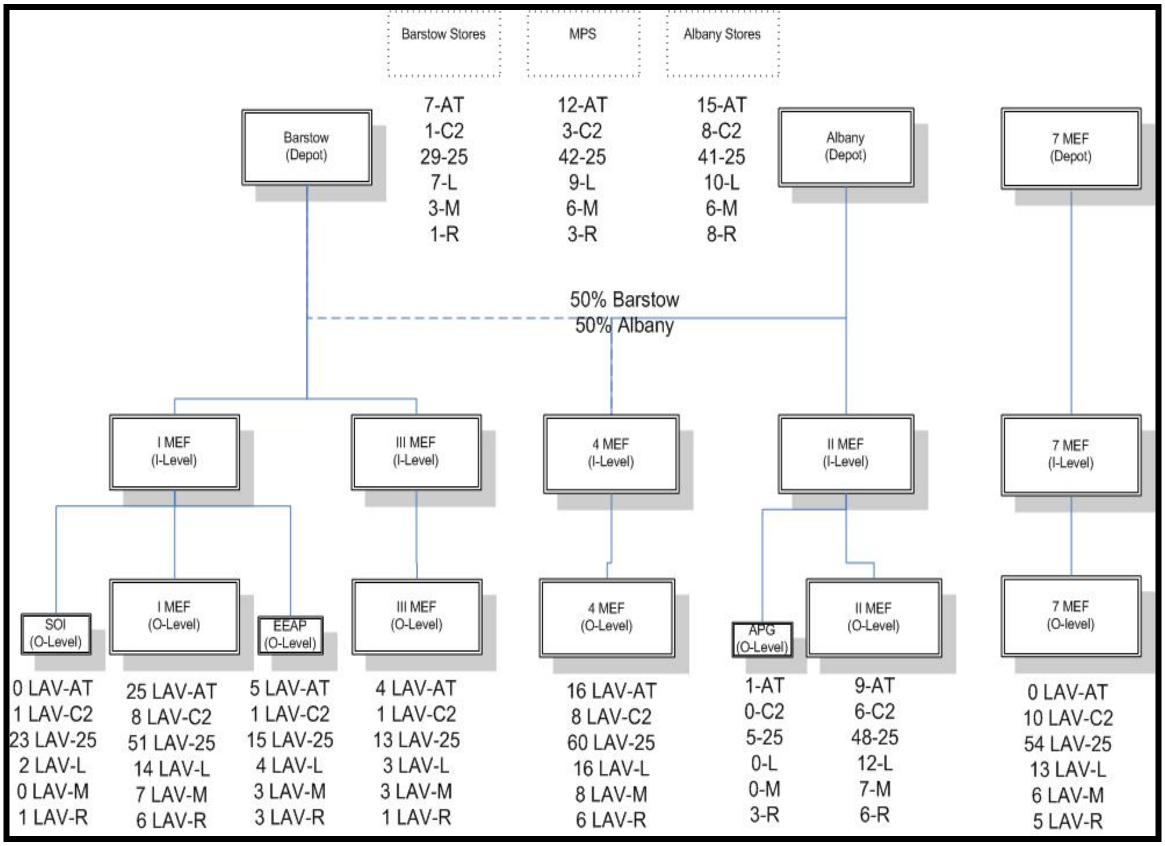

Figure 2. Base structure and system placement in the LAV model

Operational tempos for baseline models are set to USMC fleet averages. Deployed units (7 MEF) have roughly five times the usage rate as nondeployed units. Units in stores or MPS are not operated. Op-tempo for the LW-155 is assumed to be 1,000 km driven and 100 rounds fired per year for all each.

The maintenance component determines the task times and effects on the system and its subsystems upon entering maintenance actions. TLCM-AT uses part numbers (if applicable) to model preventive maintenance, partial repairs, depot upgrades, principle end-item (PEI) depot rotations, mandatory life limited removals, and unscheduled failures.

For the SOE-based AAV, LAV, and MTVR models, task times are taken from maintenance allocation charts (MAC) which are estimated by maintenance personnel. Task times are approximated as follows:

- **Tear Times:** Fifteen minutes for consumable items; 150 minutes for repairable items.
- **Default Repair Times:** Fifty days for depot level; 3.65 days for intermediate and operational level.
- **Other Repair Times:** The repair cycle time (RCT) from the Master Work Schedule (MWS) where applicable.
- **Build Times:** Only apply to AAV model where a one-day system build time is used to represent the limited technical inspection (LTI) process at the conclusion of maintenance.
- **Inspection Times:** Constant; the AAV model has a one-day system inspection time to represent problem diagnosis.

The maintenance task times in the LW-155 and JLTV models are of much higher fidelity. Inspection, tear, repair, and build times are set according to part or subsystem using both measured and estimated crew times (from LAV subsystems in the case of the JLTV).

Depot capacity constraints in the AAV, LAV, and MTVR models are determined according to the actual depot MWS for Fiscal Years (FYs) 2007-2009. For FYs 2010-2011, the 2007-2008 schedules are repeated. These are adjusted according to fleet needs. Deployed units have no depot capacity constraints; all necessary work is assumed to be completed. I-Level capacity constraints are set proportionally to the number of mechanics in the maintenance battalion table of organization (T/O): 80% for nondeployed units and 100% for deployed units. In the LW-155 and JLTV models, there are currently no capacity constraints.

In the sustainment component, a "buy upon condemnation" feature and USMC spare inventories can be controlled from the TLCM-AT analysis control panel. USMC spare inventories are apportioned in the AAV, MTVR, and LAV models as scenarios. The baseline models, instead, include an optimized spares package. The LW-155 and JLTV models also use optimized spares packages. None of the models currently feature any depot upgrade programs or PEI rotations, although the tool provides this capability.

Shipping-time distributions for the AAV, MTVR, and LAV models are fit to historical data. Many fits are lognormal. The LW-155 and JLTV models use appropriate constant times for shipping between maintenance levels.

In the cost component, TLCM-AT enables computation of the following total life-cycle costs:

- Initial provisioning
- Spares storage
- Spares replenishment
- Shipping
- Supply administration
- Manpower
- Training
- Test equipment maintenance
- Test equipment space
- Development

Costs may be displayed as a function of time, as totals, and per operating hour. Furthermore, costs related to individual Line Replaceable Units (LRUs) may be analyzed. TLCM-AT features include:

- Uses Marine Corps' automated SOE Decision Support Tool.
- Database structure provides for plug-ins and simulation of numerous systems and platforms.
- Provides "what if" simulation scenario management for analysis of life-cycle sustainment forecasts.
- Includes operation and maintenance models.
- Forecasts by part numbers or serial numbers by equipment group.
- Maintenance modeling–phased inductions include three options: scheduled or preventative, causal, or opportunistic.
- Life-cycle impact assessments include three aging options: aging by assembly, location, and repair interval.
- Ability to initialize system state, component state, and life-cycle metric prediction.
- Operational variations by location.
- Part interchangeability and substitutability rule manipulation.
- Repair capacity evaluation, which allows for measuring total repair cycle time for individual LRUs.
- Cycle time evaluation (repair, transportation, and order lead time).

- Up to three maintenance levels.
- Time-dependent forecasting, which allows for any model outputs to be displayed in time-based format.

With the TLCM-AT tool, users may quantify life-cycle costs and impacts due to management decisions regarding equipment configuration changes, remaining-life rules modifications, alternate sparing strategies, adjusted operating hours programs, modified repair concept, and age and reliability factors. Applications for use include:

- Maintenance concept modifications.
- Deployment strategy assessments (operations).
- Systems degraders' assessment (sensitivity).
- Reliability modifications impacts (build and configure).
- Supply chain alternatives (supply, stock, and resupply).
- PEI rotations (fleet management).

Military services use a complex system of maintenance and supply to manage reparable items in their inventories using two key concepts: level of repair and indentures.[6]

Levels of repair are differentiated by their varying the number of resources and capabilities. Organizational (or operational) repairs are closest to the weapons system and consist mainly of diagnostics and remove-and-replace maintenance of the weapons system itself. Depot-level maintenance exists farthest from the weapons system. Depot-level maintenance includes diagnostics, overhaul, and remanufacturing. One or more levels of intermediate repair may exist between organizational and depot-level maintenance. TLCM-AT models three levels of repair: operational, intermediate and depot.

Reparable items consist of smaller subcomponents, forming an indenture relationship between parent parts and child parts. Having an indenture-level organizational structure means an item can be repaired at some intermediate level by removing and repairing components and subcomponents. The indenture relationship

---

[6] Bradley E. Anderson,. Marvin A..Arostegui, and David L. Lyle, "Methods for Conducting Military Operations Analysis," Military Operations Research Society, LMI Research Institute, McLean, Virginia, 2007, p. 352.

requires logisticians and supply personnel to balance stock inventories to stock the right expensive items and smaller, cheaper subcomponents. These items must also be placed at the right level of repair. The TLCM-AT model uses the indenture-level concept. Figure 3 shows the basic structure of the indenture levels modeled in TLCM-AT.

Indenture Levels

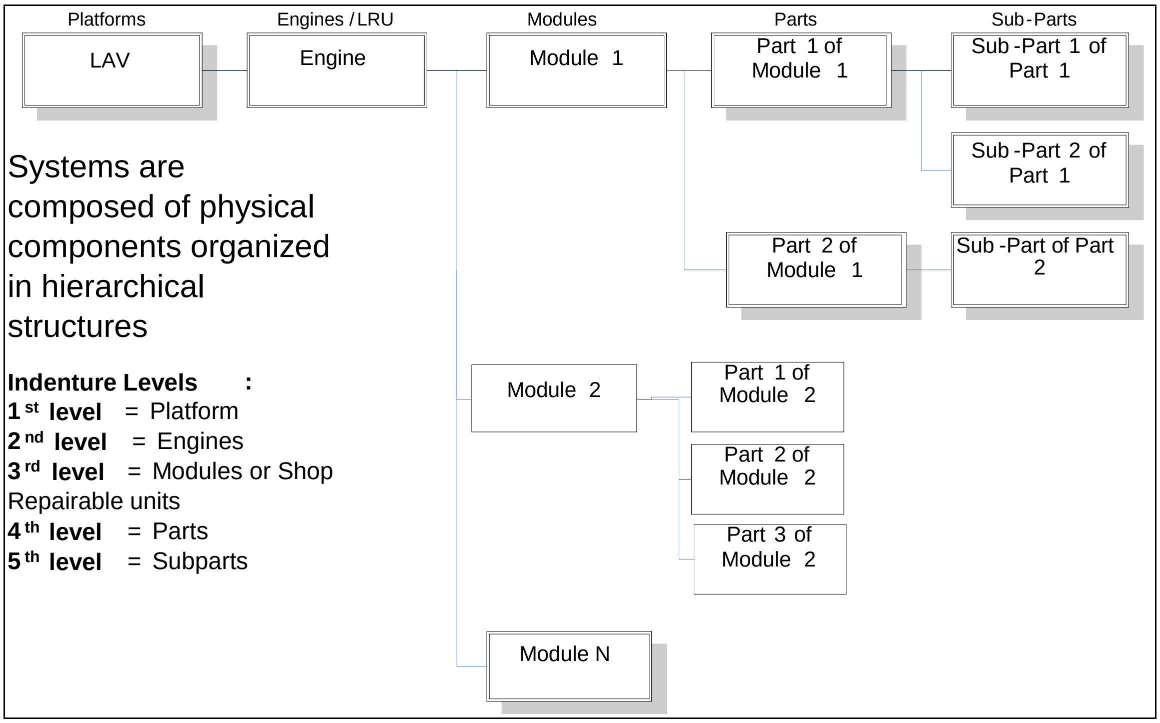

Figure 3. TLCM-AT indenture structure

The TLCM-AT model's structure and organization enables the Marine Corps to model the myriad of industry-accepted elements that directly affect the Ao of a system, and easily run "what if" scenarios by manipulating data inputs to examine the long-term effects to life-cycle elements. TLCM-AT provides a common tool across the Marine Corps to meet enterprise-level concerns and identify where improvements can be made with regard to process and policy, asset management and performance-based logistics (PBL) validation.

THIS PAGE INTENTIONALLY LEFT BLANK

III. SCENARIO DEVELOPMENT AND DATA GENERATION

A. INTRODUCTION

This chapter explains the scenario and the data generation for use in the post experiment analysis. The concepts of DOE and NOLHs aid in the analysis of a complex model like TLCM-AT. Data is generated and automated to support the analysis. A fictional LAV scenario is used as the basis for the simulation.

B. DESIGN OF EXPERIMENTS

TLCM includes everything from the design, engineering, and manufacturing, to the disassembly and disposal of a system. Life-cycle simulation tools are complex and contain many factors or variables. To identify robust mixes of these factors and their synergies, over many scenarios, experimental designs are needed. The DOE concept allows researchers to simultaneously vary the levels of factors (or inputs), resulting in an estimate of factor effects on response variables (outputs).

To understand the contributions of individual factors, each factor is varied to produce all possible combinations. This is sometimes referred to as a full-factorial design, which considers each possible factor combination. The number of simulation runs required in a full-factorial design increases exponentially with the number of factors. For example, a full-factorial design of 12 factors, each having ten levels, requires 10^{12} (one trillion) runs. Running this many combinations is impractical. To avoid this difficulty, a base case scenario may be compared to others by changing one factor at a time. While this is a time-saving approach, estimates of interactions (synergies) among the different factors may be overlooked, and conclusions may be inaccurate. Fortunately, these difficulties can be mitigated by applying the NOLH.

NOLHs allow exploitation of a large portion of the factor space without requiring an unrealistic number of runs. These designs are *nearly* orthogonal because a small degree of nonorthogonality is allowed in order to achieve better space-filling. A design matrix is referred to as nearly orthogonal if the maximum absolute pair-wise correlation between any two columns is less than .05. The small sample of the NOLH is seen in Table 1, and the full NOLH can be found in the Appendix.

low level	**1**	**1**	**1**	**0.5**	**0**
high level	**30**	**30**	**30**	**1.5**	**10**
decimals	**0**	**0**	**0**	**4**	**4**
factor name	**Spares**	**IQ**	**I Cap**	**Deg**	**ST**
	8	14	12	0.9531	3.3594
	27	10	13	0.9609	0.9375
	14	23	1	0.7734	4.1406
	21	27	10	0.8672	4.375
	1	12	17	0.7344	1.0156
	21	13	21	0.5078	3.9844
	12	30	23	0.7891	1.5625
	18	21	27	0.5625	3.4375
	2	2	8	0.7031	1.9531
	30	3	7	0.7656	1.1719
	2	29	15	0.7813	3.125
	28	30	8	0.8828	1.4063
	15	8	29	0.6797	4.0625
	23	7	28	0.8516	0.8594
	8	16	29	0.7266	4.6875
	24	23	30	0.5313	1.7188

Table 1. Spreadsheet containing a small portion of the NOLH for this thesis

Each row in the yellow-shaded section in Table 1 represents one design point or simulation run (Spares = number of spares, IQ = induction quantity, I Cap = I-level capacity, Deg = degradation time, ST = service time). The number under each column represents the level of that factor during that particular design point's simulation run. This analysis required 129 rows (design points) in the yellow-shaded area. After all design points are replicated, the effects of each factor and factor combination can be analyzed. Figure 4 shows all two-way input combinations. Each cell shows all input combinations between the factors on the x-axis and the factors on the y-axis.

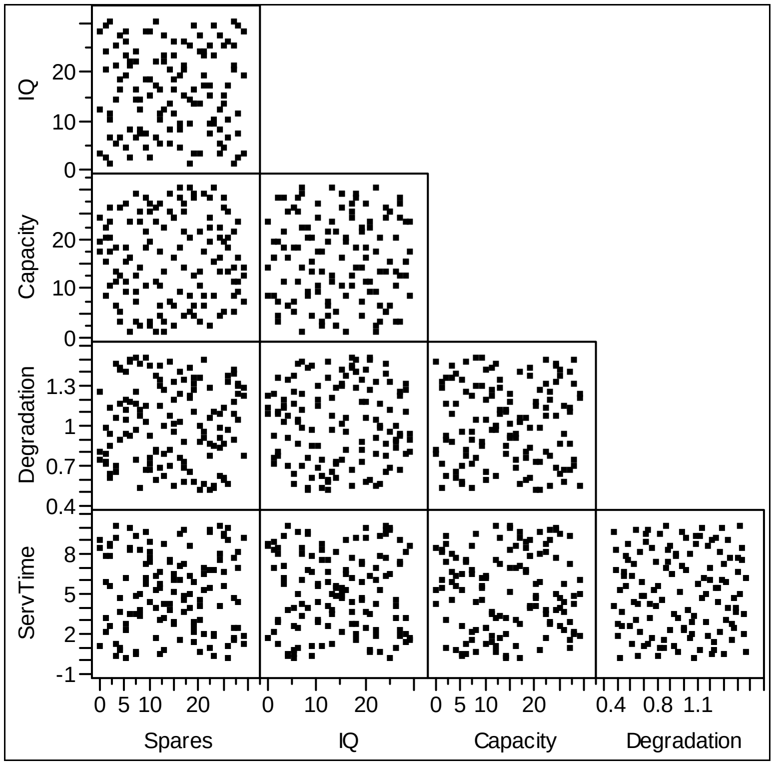

Figure 4. All two-way input combinations

C. DATA GENERATION AND FLOW

This section briefly describes the data generation. TLCM-AT uses a Microsoft Access database for both inputs and outputs (both are contained in the same file). Varying levels of multiple factors over many design points can be tedious, time-consuming, and virtually impossible for large-scale changes. To alleviate this problem, a procedure is developed to efficiently change the levels of multiple factors in the database, send them to the TLCM-AT for a simulation run, and gather the results. This procedure uses a Java program. A representation of the data generation is provided in Figure 5.

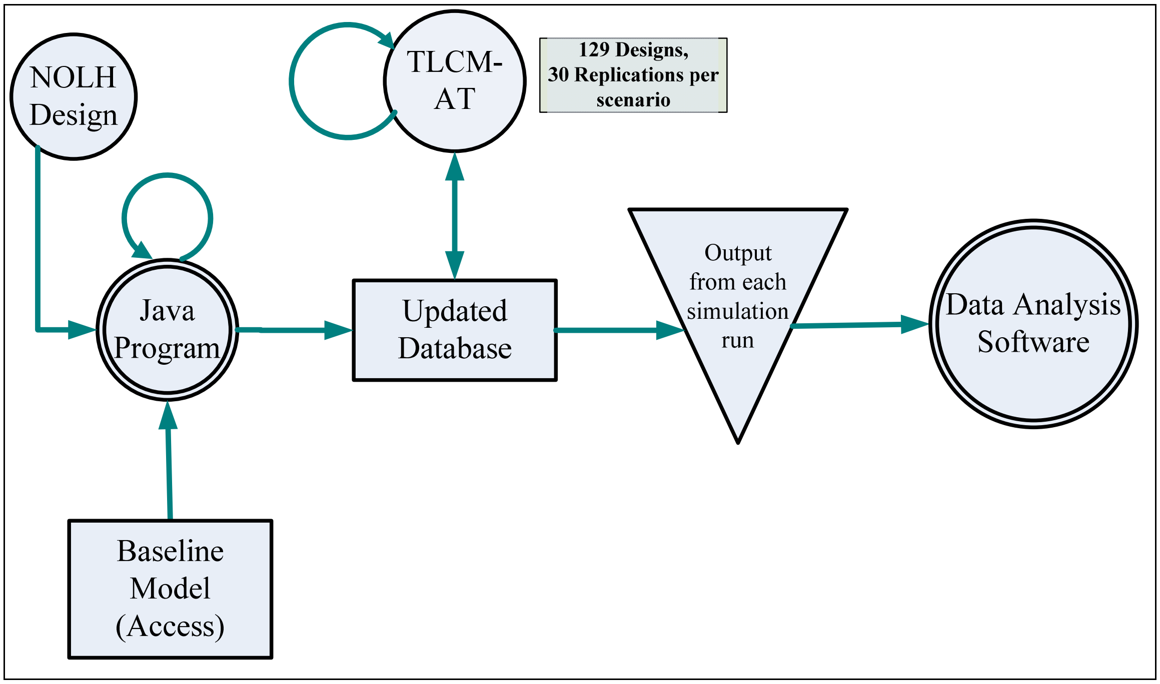

Figure 5. Diagram of data generation process

The Java program receives the NOLH design matrix and the baseline database for each scenario. The program reads the first design point row and the levels for each factor and then goes into the database to adjust each factor in the appropriate input table. Next, the updated database is sent to TLCM-AT for a simulation run on that single design point. The output data generated from the simulation run is then collected by the program and written to a comma-separated-file. This procedure is repeated automatically for each design point. Upon completion of all simulation runs, a single file containing the data of interest for each design point is available for post-analysis. Detailed code for this process can be found in an NPS thesis scheduled for completion in September 2008, by Lieutenant Commander Alberto A. Garcia, United States Navy.

D. SCENARIO DEVELOPMENT

This section explains the scenarios used for this thesis. These scenarios represent possible COAs for a notional contingency deployment for the LAV. Each scenario is modeled separately in four different databases to represent the particular plan for the replacement of two trouble parts. The scenarios were modeled by a modeler and analyst from Clockwork Solutions (Dr. Peter Figliozzi).

1. Notional Background

The Marine Corps is given a warning order to rapidly deploy for combat operations in a tropical region. The mission details and terrain drive the Marine Corps to include at least a battalion of LAVs in the force mix. The deployment consists of a lead LAV battalion and a follow-on LAV battalion.

From historical data of combat operations in hot, humid environments, LAV maintainers anticipate numerous unscheduled removals rates of two computerized LRUs on the LAV weapons system:

- OT 702275001, SENSOR UNIT, LASER DESIGNATOR
- OT 702261001, CONTROL DISPLAY UNIT

The problem with the computerized LRUs first becomes apparent only a few weeks after the lead battalion's arrival in theater. This maintenance problem is a detriment to the Marines' ability to accomplish their mission. Given time to assess the situation, three COAs are suggested:

COA 1: Send a large number of spares with the follow-on battalion.

COA 2: Invest in improved LRUs. The research and development (R&D) cost for the one-month R&D program is $1M, and the new LRUs cost an additional 1.5 times the cost of the old type. Bring a lesser number of the improved spares and install them whenever the old type is removed. When the old type is condemned, buy the new type.

COA 3: A variant of COA 2, except that the old type is purchased whenever the LRUs are condemned. No money is invested in the new LRUs. The idea is to save some money, while maintaining the same level of Ao and maintenance utilization.

2. Simulation Scenarios

This subsection provides some technical details of each of how the scenarios (or COAs) are modeled in the TLCM-AT database. Four scenarios are used. The first is a baseline scenario with no corrective action taken (maintaining the status quo).

Scenarios 1-3 will be compared against the baseline scenario. A Stock Record Account Number (SRAN) is used to indicate the location of the LAV. For example, SRAN 10001 indicates that the LAV is located with I-MEF, and SRAN 10007 indicates that the LAV is located with a deployed MEF. Each scenario is detailed below:

LAV 3042 v5 Tropical Baseline Scenario:

This is the baseline scenario that maintains the status quo:

- Baseline model is LAV 3042 v5 (SOE based, LRU-only model).
- SRAN 10007 LAVs are turned off (zero optempo) except during the following times: 2008 Q4 – 2010 Q1 inclusive (the contingency period).
- The optempo for all SRAN 10007 LAVs during the contingency period is 2,000 hours/year.
- An initial force of 88 LAVs (including 45 LAV-25s) at SRAN 10007 operates throughout the contingency period.
- All of SRAN 10001 LAVs (111 total LAVs including 51 LAV-25s) redeploy to SRAN 10007 in 2009 Q1. In 2010 Q1, they redeploy back to SRAN 10001. Thus, they are active in SRAN 10007, together with the initial force, from 2009 Q1 – Q4 inclusive.
- The failure rate for OT 702275001, SENSOR UNIT, LASER DESIGNATOR, is set to 4.3 per 10,000 operating hours, only at SRAN 10007. Elsewhere, it is 0.43.
- The failure rate for OT 702261001, CONTROL DISPLAY UNIT, is set to 4.2 per 10,000 operating hours, only at SRAN 10007. Elsewhere, it is 0.42.

LAV 3042 v5 Tropical – Scenario 1:

This scenario represents the plan to bring old-type spares with the follow-on battalion:

- Add numerous amounts of spares to the deployment.
- Quantity of 100 of the two troubling LRUs are added to SRAN 10007 as spares, during 2009 Q1.

LAV 3042 v5 Tropical – Scenario 2:

This scenario includes investment in improved SENSOR UNIT and CONTROL DISPLAY UNIT; however, limited quantities are immediately available (50 of each for the deployment). They are taken on deployment as spares. Additionally, when the old types are condemned, the new type is bought as replacements.

- Added OT 7022275002 and 702261002 to ***Object type** table (duplicates of 001 versions, added a "2" to the end of the part number to differentiate it from the old part).
- Changed ***Preferred buys** table for 001 type to 002 type.
- Added 002 type to ***Preferred buys** table.
- Duplicated ***Server times** table for 002 types (made same as 001 types).
- Changed ***Unscheduled removal rates** table to 0.4 for both 002 types (all locations).
- Changed ***Slots by type** table for LAV-25 to prefer 002 variant.
- Made price for type 002 in ***LCC costs** table 1.5 times the 001 price.
- Quantity of 50 of the new type (002) of the two trouble LRUs added to SRAN 10007 as spares, 2009 Q1.

<u>LAV 3042 v5 Tropical – Scenario 3</u>:

This scenario is the same as COA 2, except the initial purchase of 50 new 002 types occurs only once. No new types are ever purchased upon condemnation (only the 001 types are purchased, whenever a 001 or 002 type is condemned).

- Copied COA 2 database to create COA 3 database.
- Changed ***Preferred buys** table for 001 type back to 001 type.
- Changed ***Preferred buys** table for 002 type to 001 type.

E. SIMULATION RUNS

Five factors are varied during each scenario. The levels of each factor are summarized in Table 2:

FACTOR	HIGH RANGE	LOW RANGE	DESCRIPTION
Spares	1	30	Spares level set to the value in the NOLH column
Induction Quantity	1	30	Induction Quantity set to the value in the NOLH column
I-Level Capacity	1	30	Capacity at the I-Level set to the value in the NOLH column
Degradation Rate	0.5	1.5	Unscheduled Removal Rate multiplied by the value in the NOLH column
Service Time	0	10	Service Time (time to repair part) multiplied by the value in the NOLH column

Table 2. Range of changes for the factors studied.

The level of the five factors is adjusted for 25 LRUs, which are chosen as the top 25 degraders. They are the 25 parts that cause the most problems during the life-cycle of the LAV-25 in the baseline model. The top degraders are ranked using a formula provided in the final project report issued by Clockwork Solutions on 31 December 2007:

Score = (Waiting time) * (Requests) * (Unavailability +1)

Waiting time is the average logistics response time. *Requests* is the number of times the part is requested by the fleet. *Unavailability* is the fraction of part-needed-but-not-spared occurrences by location. Unity (+1) is added to *Unavailability* so that parts with frequent failures are appropriately spared.

The primary measure of effectiveness (MOE) is Ao. After each simulation run, Ao is gathered for each quarter, for a period of five years from the *out Availability output table from the TLCM-AT. (It should be noted that the *out Availability table gives the Ao as the mean of the number of replications.)

Each of the four scenarios (the baseline plus the three COAs) is simulated in TLCM-AT using the DOE concept and the NOLH, as previously discussed. For each scenario, the 129 design points are formed from the same NOLH design matrix. For each design point, 30 replications are completed. The constraint on the number of replications is run time. Each design point takes approximately 30 minutes to run. In summary:

- Total design points: 4 scenarios with 129 designs point each = **516**
- Total replications: 129 design points with 30 replications = **15,480**
- Total time for all simulation runs: 516 design points for 30 minutes each = **258** hours (10+ days).
- Simulation runs executed on two standard desktop processors for a total duration of approximately five days.

IV. ANALYSIS

A. INTRODUCTION

This chapter describes the data collection and post processing. In accordance with the scenarios described in Chapter III, the analysis centers on evaluation of Ao at the end of quarters 12 and 20: quarter 12 is the end of the forecasted end of the contingency, and quarter 20 is the end of the five-year period of evaluation (five quarters of high-tempo operation and normal operation for the remaining time). Section B contains an interpretation of the results produced by TLCM-AT after running each scenario, and a discussion of the conclusions that may be drawn from the results. Section C gives detailed analysis and discussion of the results produced after simulation runs with DOE implementation. Throughout the analysis, insight into the TLCM process is more important than specific numerical results. The focus of this chapter is to show how TLCM-AT, combined with DOE, can be used by analysts to maximize the insight drawn from discrete event simulation.

B. TLCM-AT RESULTS

The analysis begins by examining TLCM-AT as a stand-alone tool, without implementation of DOE. Each scenario run is simulated through TLCM-AT using 100 replications. At the completion of the four simulation runs (one for each COA and one for the baseline), post-processing applied with TLCM-AT's graphical-user-interface (GUI) and its built-in analytical utilities. The TLCM-AT graphs are best viewed in color.

In an example of quick-turn analysis using TLCM-AT, a cost comparison is first completed. Results from each COA, as they relate to cost, are depicted in Figures 6 and 7.

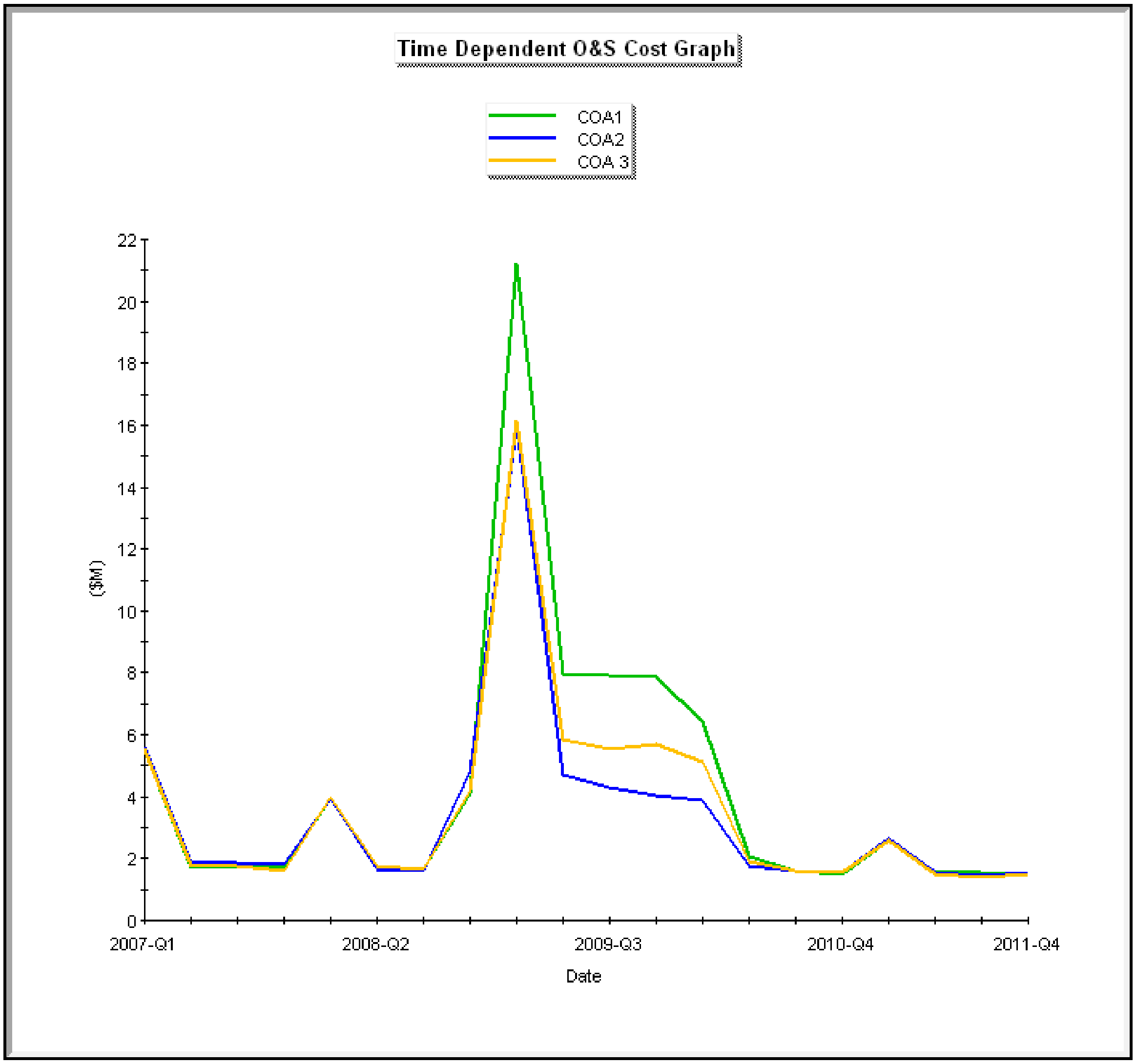

Figure 6. Operation and Sustainment (O&S) cost graph

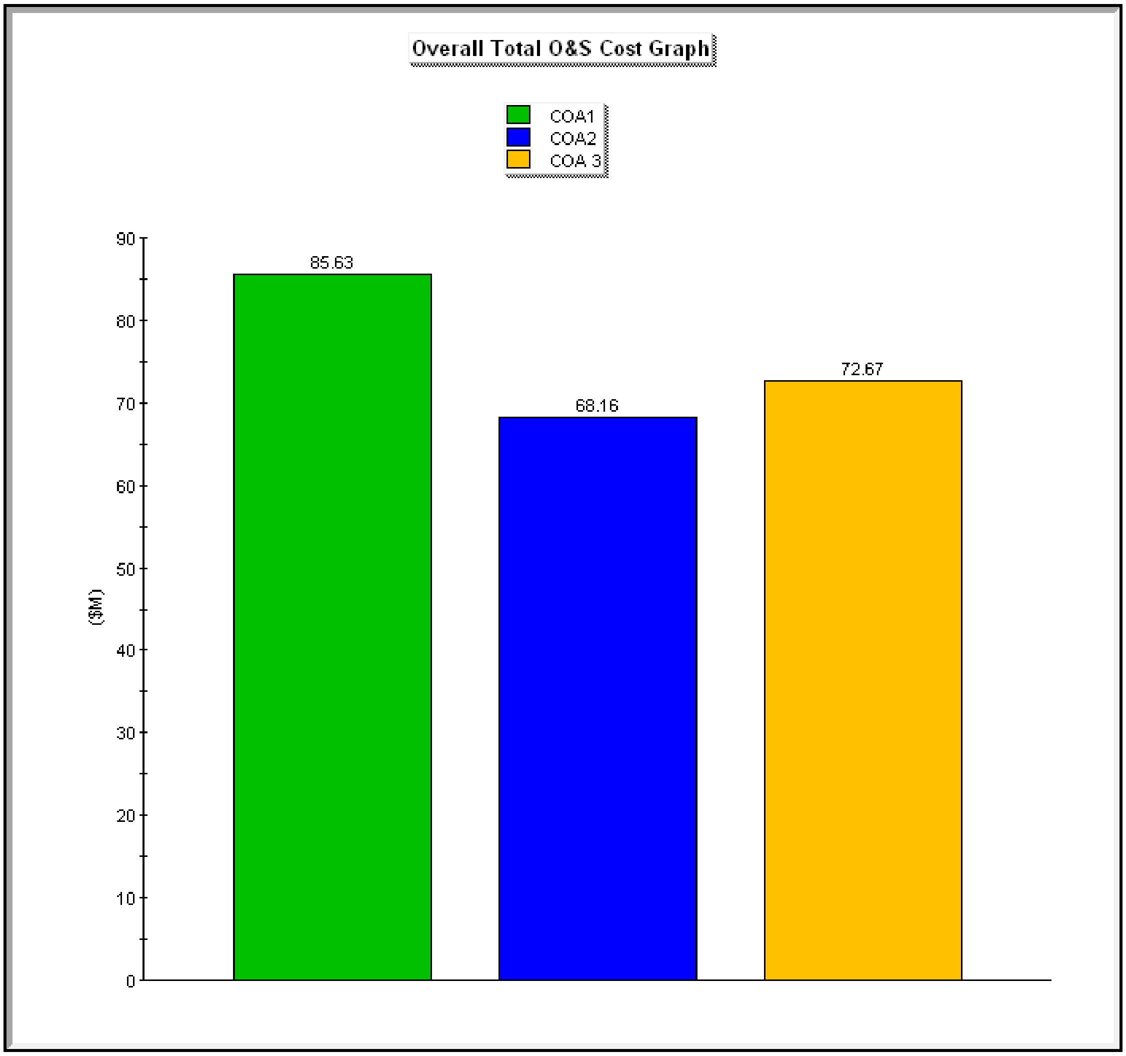

Figure 7. Overall total O&S graph

Figure 6 represents time-dependent O&S costs for spares replenishment for each COA over the five-year period. The peak evident in the graph indicates the time period in which the contingency operations are being conducted. Figure 7 depicts the overall total O&S cost for each COA. COA 2 saves \$3.2 million compared to COA 3 and \$15.8 million compared to COA 1. The results quantify the immediate value of the engineering change program (ECP) to improve the two trouble parts. Even though the price of improved parts is 50% greater than the price of the old parts, the ECP immunizes the LAV-25 fleet against humidity problems in the future and saves money in the meantime.

Next, a comparison is done to reflect how each COA affects Ao. This comparison includes the baseline scenario, representing the decision to maintain the status quo. Figure 8 depicts time-dependent Ao of the LAV-25 for each COA.

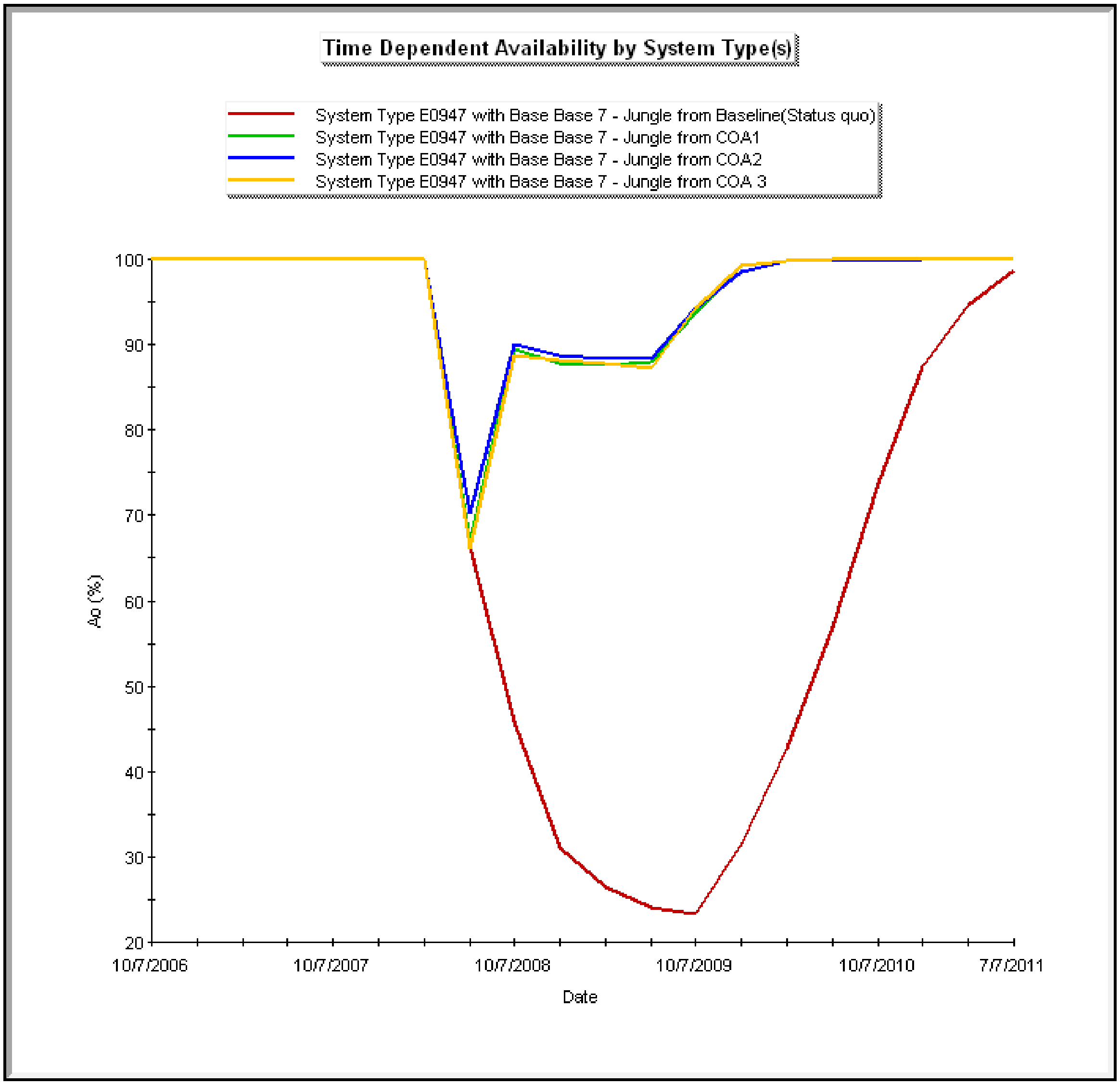

Figure 8. Time-dependent Ao

As Figure 7 reveals, each COA (1-3) maintains relatively the same Ao throughout the contingency timeframe, as well as throughout the full 20-quarter period. Also, maintaining the status quo will greatly reduce Ao during the contingency, as depicted with the red (lowest) line in Figure 7. In regard to Ao, it is evident that taking some action, whether it is COA 1, 2, or 3, is much more preferable to maintaining the status quo.

Adding more old spares or introducing new spares into the maintenance system will undoubtedly have an effect on a repair facility. TLCM-AT can display this effect by examining the number of maintenance tasks performed during the contingency on the laser designator unit. COA 2 clearly produces the lightest workload for the maintenance facility, as depicted by the blue (lowest) line in Figure 9. Base Shop 7 in Figure 9 represents the repair facility designated for maintenance on the LAV-25s during the contingency.

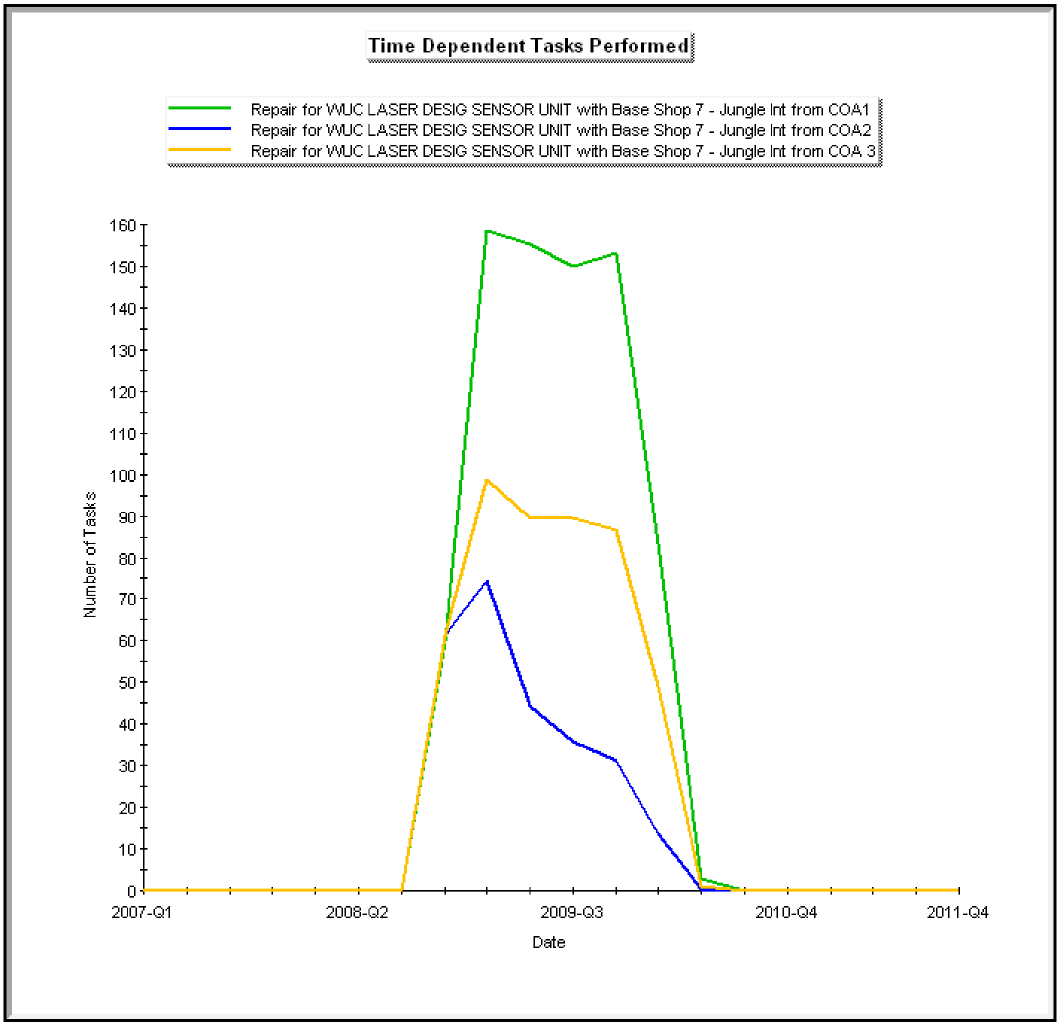

Figure 9. Number of maintenance tasks performed on the laser designator unit

From the analysis, it is evident that COA 2 is the preferred COA. It has lower overall O&S costs for spares replenishment, and provides the least amount of impact on the repair facility. These effects are accomplished with no negative impact on Ao.

The preceding analysis and discussion is an example of the quick-turn type of analysis that can be accomplished with TLCM-AT. However, it must be remembered that each COA had to be modeled separately in the Access database before execution of the simulation. Depending on the user's familiarity with the TLCM-AT modeling process, this could be a fairly time-consuming task.

C. TLCM-AT WITH DOE IMPLEMENTATION

This section discusses the analytical process and results after simulation with DOE implementation and insights gained. As in the previous analysis, the focus in this section is directed at the Ao in quarters 12 and 20. This section contains regression analysis, t-Tests for two-sample means and an evaluation of the best design points. It should be noted here that the practical change in Ao after the simulation runs is very minimal. In other words, changes are too small to effect a decision. This result is in line with the results seen in Section B. The ranges of Ao are depicted in Table 3.

	Quarter 12				Quarter 20			
	Baseline	COA1	COA2	COA3	Baseline	COA1	COA2	COA3
Max Ao	82.18%	83.00%	82.83%	83.15%	90.19%	90.31%	90.11%	90.41%
Min Ao	80.41%	80.39%	81.23%	80.76%	87.43%	88.73%	88.84%	88.69%

Table 3. Ao ranges per COA for quarters 12 and 20

The maximum and minimum Ao in all simulation runs, across all COAs and design points is depicted in Table 4.

Quarter 12		Quarter 20	
Max Ao	83.15%	Max Ao	90.41%
Min Ao	80.39%	Min Ao	87.43%

Table 4. Ao ranges across all COAs and design points

1. Regression Analysis

Regression is a technique used for the modeling and analysis of numeric data consisting of values of a dependent response variable (Ao) and one or more independent explanatory variables (spares, induction quantity, capacity, degradation time, service time). Ao is the only response variable used because of time constraints to complete this study. The dependent variable in the regression equation is modeled as a function of the independent variables. Regression analysis shows the independent variables that are statistically significant to the dependent variable. Among many independent variables, only a few of them may be significant in determining the measure of interest.

This analysis uses stepwise regression to evaluate the data obtained from the simulation runs of the COAs discussed in Chapter III. The basic procedures for stepwise regression involve:

1. Identifying an initial model.
2. Iteratively stepping, or repeatedly altering, the model at the previous step by adding or removing an independent variable.
3. Terminating the search when stepping is no longer possible given the stepping criteria or when a specified number of steps have been reached.

The forward selection approach is used in this analysis. Forward selection involves starting with no variables in the model and trying out the variables one by one, and including them if they are statistically significant.

Thirty-two regression models are evaluated. One model is developed for quarter 12 and another for quarter 20 for each scenario. Regression determines significant factors affecting Ao, and the variance in Ao, explained by the five varied factors. The amount of variance explained by the factors is represented by the coefficient of determination, or R^2; as the R^2 increases, the amount of explained variance in the statistical model increases. A low R^2 indicates there could potentially be more factors affecting the outcome than those modeled. The R^2 from all stepwise regressions is shown in Table 5.

COA	QTR	Main Effects	2-way Interaction	3-way Interaction	Quadratic
Base Scenario	12	0.47	0.53	0.56	0.59
Base Scenario	20	0.65	0.74	0.79	0.81
Scenario 1	12	0.61	0.71	0.75	0.76
Scenario 1	20	0.04	0.18	0.22	0.24
Scenario 2	12	0.15	0.26	0.32	0.4
Scenario 2	20	0.02	0.05	0.2	0.23
Scenario 3	12	0.3	0.47	0.51	0.62
Scenario 3	20	0.02	0.03	0.04	0.07

Table 5. R^2 from all stepwise regressions

Table 5 shows relatively low R^2 values for scenarios 1-3, especially during quarter 20. Furthermore, the R^2 increases in all cases as interaction and polynomial (quadratic) terms are added to the model. The increase in R^2 shows that including only main effects does not capture the complete picture; interaction terms reveal synergies between the modeled factors. Practically, this shows that adjusting only one or two factors independently may not be the best solution if seeking to maximize Ao. Furthermore, this form of regression cannot adequately capture the richness of TLCM-AT; other factors added to the model will increase R^2. In the cases where R^2 is low, the results show that other factors should be considered.

Scenario two quarter 12 is used as an example. The following stepwise regression includes all two-way interaction and three-way interaction terms. Table 6 shows the summary of fit and parameter estimates produced from the regression are shown in Table 7.

Summary of Fit	
RSquare	0.400167
RSquare Adj	0.216545
Root Mean Square Error	0.00252
Mean of Response	0.822325
Observations (or Sum Wgts)	129

Table 6. Summary of fit for scenario 2 quarter 12

Parameter Estimates				
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	0.8214981	0.001445	568.48	<.0001*
Spares	0.0001396	2.959e-5	4.72	<.0001*
IQ	1.4267e-5	2.811e-5	0.51	0.6129
Capacity	-0.000043	2.723e-5	-1.58	0.1176
Degradation	-0.000271	0.000799	-0.34	0.7355
ServTime	-0.000042	8.633e-5	-0.49	0.6283
(Spares-15.5039)*(IQ-15.5039)	-4.132e-7	3.015e-6	-0.14	0.8913
(Spares-15.5039)*(Capacity-15.5039)	-2.522e-6	4.275e-6	-0.59	0.5566
(Spares-15.5039)*(Degradation-1.00001)	0.0002071	0.00011	1.88	0.0634
(Spares-15.5039)*(ServTime-5.00001)	0.0000195	9.31e-6	2.09	0.0388*
(IQ-15.5039)*(Capacity-15.5039)	-4.408e-6	3.632e-6	-1.21	0.2279
(IQ-15.5039)*(Degradation-1.00001)	-0.000269	0.000133	-2.03	0.0452*
(IQ-15.5039)*(ServTime-5.00001)	4.8612e-7	9.094e-6	0.05	0.9575
(Capacity-15.5039)*(Degradation-1.00001)	0.0000949	8.844e-5	1.07	0.2859
(Capacity-15.5039)*(ServTime-5.00001)	-1.661e-6	0.000012	-0.14	0.8894
(Degradation-1.00001)*(ServTime-5.00001)	0.0002695	0.000295	0.91	0.3628
(Spares-15.5039)*(IQ-15.5039)*(Capacity-15.5039)	-1.221e-7	4.666e-7	-0.26	0.7942
(Spares-15.5039)*(IQ-15.5039)*(Degradation-1.00001)	-2.661e-5	1.363e-5	-1.95	0.0537
(Spares-15.5039)*(IQ-15.5039)*(ServTime-5.00001)	1.7182e-6	1.112e-6	1.55	0.1255
(Spares-15.5039)*(Capacity-15.5039)*(Degradation-1.00001)	6.7712e-6	1.366e-5	0.50	0.6211
(Spares-15.5039)*(Capacity-15.5039)*(ServTime-5.00001)	-1.348e-7	1.369e-6	-0.10	0.9218
(Spares-15.5039)*(Degradation-1.00001)*(ServTime-5.00001)	-0.000046	3.86e-5	-1.19	0.2371
(IQ-15.5039)*(Capacity-15.5039)*(Degradation-1.00001)	-2.051e-6	1.385e-5	-0.15	0.8826
(IQ-15.5039)*(Capacity-15.5039)*(ServTime-5.00001)	-1.985e-6	1.198e-6	-1.66	0.1007
(IQ-15.5039)*(Degradation-1.00001)*(ServTime-5.00001)	-5.255e-5	3.982e-5	-1.32	0.1900
(Capacity-15.5039)*(Degradation-1.00001)*(ServTime-5.00001)	0.0000417	0.000039	1.07	0.2866
(Spares-15.5039)*(Spares-15.5039)	-1.067e-5	4.502e-6	-2.37	0.0197*
(IQ-15.5039)*(IQ-15.5039)	-5.518e-6	4.21e-6	-1.31	0.1931
(Capacity-15.5039)*(Capacity-15.5039)	-8.746e-7	4.012e-6	-0.22	0.8279
(Degradation-1.00001)*(Degradation-1.00001)	0.0050247	0.003508	1.43	0.1553
(ServTime-5.00001)*(ServTime-5.00001)	4.5964e-5	3.744e-5	1.23	0.2225

Table 7. Parameter estimates for scenario 2 quarter 12

Number of spares is the dominant factor in the model. Forty percent of the variance is explained. Table 6 shows the summary of fit and parameter estimates produced from the regression are shown in Table 7.

The significant factors in determining Ao (as shown in Table 7 with accompanying asterisk) are:

- Spares
- Spares × Spares
- Spares × Service Time
- Induction Quantity × Degradation

A final model is created by removing all insignificant factors. Induction Quantity × Degradation is now an insignificant factor. The R^2 drops from 40% to 24% of the variance explained by the model. Number of spares is the dominant factor in the final model. Table 8 shows the summary of fit and parameter estimates produced from the regression are shown in Table 9.

Summary of Fit	
RSquare	0.242189
RSquare Adj	0.224002
Root Mean Square Error	0.002508
Mean of Response	0.822325
Observations (or Sum Wgts)	129

Table 8 Final model summary of fit for scenario 2 quarter 12

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.8213247	0.000523	1571.2	<.0001*
Spares	0.0001175	2.611e-5	4.50	<.0001*
(Spares-15.5039)*(ServTime-5.00001)	2.2623e-5	8.165e-6	2.77	0.0064*
(Spares-15.5039)*(Spares-15.5039)	-1.148e-5	3.434e-6	-3.34	0.0011*

Table 9 Final model parameter estimates for scenario 2 quarter 12

The significant factors in determining Ao (as shown in Table 9 with accompanying asterisk) are:

- Spares
- Spares × Spares
- Spares × Service Time

The coefficients are small; this indicates that these terms, while statistically significant in the model, have minimal practical impact on Ao. In other words, the increase in Ao for each spare added is too small to effect a decision. Similar conclusions are drawn from the other COAs as well.

2. Two-Sample Comparison

Following regression analysis, paired two-sample t-Tests are done between each scenario. The purpose of a t-Test is to determine whether or not two population means are equal. The two-sample t-Test is performed on two data sets that are assumed to have been drawn from populations that follow a normal distribution with constant variance. However, for sufficiently large samples there are moderate to robust departures from these assumptions. The data sets used here are the Ao values generated for each scenario over the 129 design points. Six t-Tests are completed to cover all possible combinations:

- Base – Scenario 1
- Base – Scenario 2
- Base – Scenario 3
- Scenario 1 – Scenario 2
- Scenario 1 – Scenario 3
- Scenario 2 – Scenario 3

In each test, the hypothesized mean difference is zero (no difference in population means). Tables 10 and 11 depict the results of all paired two-sample t-Tests for differences in Ao after quarters 12 and 20, respectively.

t-Test: Paired Two Sample for Means Quarter 12		
	Base	***COA1***
Mean	0.811409591	0.818230432
Variance	1.1044E-05	2.78253E-05
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**4.65353E-33**	
t Critical two-tail	1.978670823	
	COA1	***COA2***
Mean	0.818230432	0.822325324
Variance	2.78253E-05	8.1056E-06
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**2.64123E-15**	
t Critical two-tail	1.978670823	
	COA2	***COA3***
Mean	0.822325324	0.821494436
Variance	8.1056E-06	1.70177E-05
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**0.022398628**	
t Critical two-tail	1.978670823	
	COA1	***COA3***
Mean	0.818230432	0.821494436
Variance	2.78253E-05	1.70177E-05
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**8.1068E-12**	
t Critical two-tail	1.978670823	
	Base	***COA2***
Mean	0.811409591	0.822325324
Variance	1.1044E-05	8.1056E-06
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**3.37578E-65**	
t Critical two-tail	1.978670823	
	Base	***COA3***
Mean	0.811409591	0.821494436
Variance	1.1044E-05	1.70177E-05
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**2.87256E-54**	
t Critical two-tail	1.978670823	

Table 10. t-Test results for difference in Ao for 12^{th} quarter

t-Test: Paired Two Sample for Means Quarter 20		
	Base	***COA1***
Mean	0.89040315	0.895018571
Variance	3.75235E-05	8.24482E-06
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**3.30143E-13**	
t Critical two-tail	1.978670823	
	COA1	***COA2***
Mean	0.895018571	0.895466579
Variance	8.24482E-06	6.7266E-06
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**0.177946263**	
t Critical two-tail	1.978670823	
	COA2	***COA3***
Mean	0.895466579	0.895127699
Variance	6.7266E-06	8.15099E-06
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**0.332484251**	
t Critical two-tail	1.978670823	
	COA1	***COA3***
Mean	0.895018571	0.895127699
Variance	8.24482E-06	8.15099E-06
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**0.745610006**	
t Critical two-tail	1.978670823	
	Base	***COA2***
Mean	0.89040315	0.895466579
Variance	3.75235E-05	6.7266E-06
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**4.25768E-14**	
t Critical two-tail	1.978670823	
	Base	***COA3***
Mean	0.89040315	0.895127699
Variance	3.75235E-05	8.15099E-06
Observations	129	129
Hypothesized Mean Difference	0	
df	128	
P(T<=t) two-tail	**1.87398E-12**	
t Critical two-tail	1.978670823	

Table 11. t-Test results for difference in Ao for 20th quarter

The low p-value calculated for each comparison reveals, in all six cases, a statistically significant difference in the mean Ao between each scenario for quarter 12. However, the higher p-values evident in quarter 20, for comparison between scenarios 1, 2, and 3, show that there is no statistically significant difference in the mean Ao.

The statistical significance shown in quarter 12 does not necessarily imply practical significance. Because the mean Ao in all cases are relatively close, the mean difference is not practically significant; going from 81.8% to 82.1% Ao is not significant enough to make practical impacts on the overall operational picture.

3. Design Point Evaluation

Additional insight can be obtained by taking a closer look at the design points producing the highest Ao. The specific factor settings in the best design points can be used to guide a decision maker when determining the level to set for specific factors. The design points, with their associated factor settings, that produced the highest Ao for scenario two are depicted in Table 12.

Rank	Design Point #	Spares	IQ	Capacity	Degradation	ServTime
			Quarter 12			
1	***86***	***22***	***24***	***6***	***0.5469***	***5.0781***
2	***71***	***10***	***18***	***10***	***1.4922***	***6.0156***
3	95	12	17	1	0.8047	5.1563
4	***53***	***10***	***7***	***18***	***1.0078***	***9.5313***
5	18	29	11	9	1.2813	4.2188
6	123	11	18	27	0.6484	4.2969
7	94	22	17	8	0.9453	6.4063
8	13	15	8	29	0.6797	4.0625
9	51	13	16	10	1.2891	5.2344
10	***58***	***20***	***13***	***4***	***1.3516***	***5.7031***
			Quarter 20			
1	***53***	***10***	***7***	***18***	***1.0078***	***9.5313***
2	***58***	***20***	***13***	***4***	***1.3516***	***5.7031***
3	102	28	21	11	1.3984	2.3438
4	***71***	***10***	***18***	***10***	***1.4922***	***6.0156***
5	68	17	8	30	1.2266	5.8594
6	69	10	4	21	1.1328	5.625
7	55	7	21	16	1.1719	9.7656
8	***86***	***22***	***24***	***6***	***0.5469***	***5.0781***
9	16	24	23	30	0.5313	1.7188
10	106	20	16	29	1.3047	2.0313

Table 12. Best design points for scenario two

Design points that rank in the top ten for both quarters are in bold italics in Table 11. As an example, if it was determined that finishing the contingency with the highest Ao was a priority, design point 86 (Spares: 22, Induction Quantity: 24, Capacity: 6, Degradation: .5469, Service Time: 5.0781) should be used as a guide to determine the optimal settings to use for the indicated factors. Design point 86 shows a high number of spares and high induction quantity provides maximum Ao. For a long-range look (20 quarters), design point 53 (Spares: 10, Induction Quantity: 7, Capacity: 18, Degradation: 1.0078, Service Time: 9.5313) should be used as a guide to determine the optimal settings. Design point 53 shows a lower number of spares, lower induction quantity and higher capacity provide maximum Ao for the full twenty quarter period. In this setting (design point 57) increasing the depot capacity allows a higher Ao while maintaining a lower level of spares and induction quantity.

THIS PAGE INTENTIONALLY LEFT BLANK

V. CONCLUSIONS

A. RESEARCH SUMMARY

This research set out to explore the capabilities of the TLCM-AT. Through development of a Java program to automate implementation of DOE with TLCM-AT, this thesis produces a thorough experimental concept and analytical technique to explore the capabilities TLCM-AT. The simulated scenarios used in this analysis form a strong foundation for further studies of TLCM-AT, using DOE to analyze life cycles. The analysis produces a process for decision makers to gain insight on weapon system life cycles using TLCM-AT. This thesis provides the following:

- A framework for using DOE with TLCM-AT.
- A structured use of TLCM-AT for USMC decision makers.
- Enhancements that enable more effective usage of TLCM-AT.

B. DOE AND TLCM-AT

TLCM-AT uses an Access database for all inputs and outputs. The Java program written for this study enables manipulation of the database and variation of input. The program development applies Java-Access interaction to change the desired elements in the database. This type of analysis required an intimate familiarity with TLCM-AT modeling logic. For example, changing induction quantity requires an update to a single input table; however, implementing a change in the number of spare parts requires updates to multiple input tables.

When performing DOE with TLCM-AT, the Java program is essential to automating the process of executing multiple design point simulations. The program is necessary to not only execute changes to the database, but to also keep track of the specific factor settings for each design point and provide the output in a form amenable to post processing.

C. TLCM-AT OBSERVATIONS

Several observations were made during the course of this research on effective use of TLCM-AT. Chapter IV shows how TLCM-AT provides a quick-turn analysis of specific “what-if” scenarios. This is accomplished mainly through use of TLCM-AT’s GUI and embedded analytical and graphing utilities. The GUI contains a scenario editor interface to allow for changes in the following areas:

- Capacity constraints
- Component induction
- Depot upgrades
- Evacuation probabilities
- Induction schedules
- Limits and screens
- Logistical consequences
- Maintenance task times
- Operational tempo
- Parts configuration
- Serial number planned usage
- Shipment times
- Spares management
- Unscheduled removal rates

TLCM-AT is a data-driven tool. The results from scenario runs are completely dependent on the quality of the data collected and modeled in the database such as miles driven, shots fired, repair times, and depot capacities. This fact demands accurate recording of usage data throughout the fleet enterprise of all weapons systems. To ensure valid results, recorded data must be accurate, timely, and modeled correctly. The modeling process requires a solid understanding of TLCM-AT data entry to represent specific scenarios.

The analysis uses the average Ao taken from each design point. Access to raw data generated from each replication, within each design point, is not available for analysis. Access to TLCM-AT raw output data would allow mapping into distributions and analysis of any outliers.

The process of conducting many simulation runs would be greatly enhanced if TLCM-AT could be run using a cluster of computers. This approach was unsuccessful due to the inability for TLCM-AT to be run in a headless mode (without a GUI). The NPS SEED Center computer cluster contains compute nodes without monitors to display the dialogue boxes required by TLCM-AT.

The final lesson learned concerns the extensive knowledge of the TLCM-AT modeling process required to simulate different scenarios. The scenarios were modeled by a modeler and analyst for Clockwork Solutions (Dr. Peter Figliozzi). While a basic knowledge of TLCM-AT's functional utilities will allow editing of various inputs through the GUI, a more robust knowledge is essential when modeling different scenarios via the database. Scenario development should be accessible to the typical user.

D. FOLLOW-ON RESEARCH

This thesis serves as a template for future life-cycle studies utilizing TLCM-AT and DOE. Real-life scenarios, or COAs, can be modeled and many different MOEs can be studied. A list of possible MOEs to study in the future is shown in Table 13.

Measure of Effectiveness/Performance	TLCM-AT Output Table	Description
Age of system	out Age by type	Age is the average hours accumulated divided by average number of objects in use.
Unscheduled maintenance events	out Aircraft events	Events include part failures, life limited, induction and repairs.
Awaiting maintenance (AWM) status	out AWM	Time each part spent in a waiting queue, such a AWM status, request and total repairs.
AWM times and probablities	out AWM times and probabilities	Time in AWM, probability towards availability and total number of requests.
Awaiting parts (AWP) status	out AWP items	Time spent in waiting queue; includes AWP status, requests and total repairs.
AWP times and probablities	out AWP times and probabilities	Time in AWP, probability towards availability and total number of requests.
Number of backordered items	out Backordered items	Average number of requests resulting in backorder.
Number of condemnations (type)	out Condemnations	Number of condemnations per type per quarter.
Number of condemnations (depot)	out Depot ENSIP and Condemnation	Average number of types sent and condemned to depot per quarter.
Time spent in depot	out Depot Flow Time	Average time spent in the depot by type.
Scheduled vs. Achieved operating hours	out Flying Hours	Scheduled and achieved hours per type per base per quarter.
Logistics response delay (LRT)	out Logistics Response Delay	Average LRT between bases.
Number of LRU removals	out LRU events	Average LRU removals due to life limits and failures by base by quarter.
Number of new buys	out New Buys	Average number of new buys by type, base and quarter.
Number of types reaching O-limit screen	out Reaching O-screen items	Average of types reaching O-limit screens by base by quarter.
Number of shipments	out Shipments	Average number of shipments between bases by type by quarter.
Number of maintenance tasks performed	out Task Performed	Average number of maintenance tasks performed by type by base by quarter.
Number of unserviceable parts	out Uninstalled-Servicable items	Average number of unservicable types by depot by week.

Table 13. MOEs for future study

It must be noted that varying factors other than those in this thesis or gathering different outputs will require additional Java coding similar to the code detailed in Lieutenant Commander Garcia’s thesis (to be completed in September 2008).

Future work could also entail a study to integrate the cluster of computers into the TLCM-AT and DOE process. This process will require a joint effort between Clockwork Solutions and SEED Center research personnel.

APPENDIX

low level	**1**	**1**	**1**	**0.5**	**0**	**1**	**1**	**1**	**0.5**	**0**
high level	**30**	**30**	**30**	**1.5**	**10**	**30**	**30**	**30**	**1.5**	**10**
decimals	**0**	**0**	**0**	**4**	**4**	**0**	**0**	**0**	**4**	**4**
factor name	**Spares**	**IQ**	**I Cap**	**Deg**	**ST**	**Spares**	**IQ**	**I Cap**	**Deg**	**ST**
	8	14	12	0.9531	3.3594	3	11	10	0.8359	5.4688
	27	10	13	0.9609	0.9375	26	15	5	0.5938	5.3906
	14	23	1	0.7734	4.1406	11	28	3	0.9141	7.2656
	21	27	10	0.8672	4.375	16	26	6	0.9375	6.3281
	1	12	17	0.7344	1.0156	3	10	20	0.6016	7.6563
	21	13	21	0.5078	3.9844	25	5	16	0.8984	9.9219
	12	30	23	0.7891	1.5625	10	28	28	0.6563	7.1094
	18	21	27	0.5625	3.4375	26	25	26	0.8438	9.375
	2	2	8	0.7031	1.9531	11	15	2	0.6953	7.9688
	30	3	7	0.7656	1.1719	25	12	13	0.6172	7.3438
	2	29	15	0.7813	3.125	15	20	7	0.8125	7.1875
	28	30	8	0.8828	1.4063	19	25	5	0.6406	6.1719
	15	8	29	0.6797	4.0625	7	2	16	0.9063	8.2031
	23	7	28	0.8516	0.8594	26	13	19	0.5859	6.4844
	8	16	29	0.7266	4.6875	2	24	20	0.9688	7.7344
	24	23	30	0.5313	1.7188	18	26	25	0.6719	9.6875
	8	6	7	1.2422	0.3906	15	13	7	1.4609	7.4219
	29	11	9	1.2813	4.2188	25	3	4	1.0781	7.8125
	6	23	9	1.0234	2.1094	13	16	10	1.2891	5.2344
	20	29	12	1.25	1.25	28	25	5	1.375	7.5
	9	7	25	1.4531	4.9219	10	7	18	1.0078	9.5313
	19	9	20	1.4219	3.75	26	4	28	1.125	9.2188
	7	22	23	1.4766	3.2813	7	21	16	1.1719	9.7656
	22	19	29	1.4844	1.875	27	26	25	1.3125	9.8438
	9	8	14	1.1094	3.2031	6	4	11	1.1797	6.0938
	28	1	14	1.0703	1.4844	20	13	4	1.3516	5.7031
	8	22	9	1.5	0.5469	4	25	13	1.4453	10
	30	28	12	1.2031	1.6406	18	20	14	1.3359	7.0313
	9	14	23	1.0547	3.5938	13	11	27	1.1406	5.5469
	19	14	30	1.1953	4.8438	17	4	18	1.0156	6.9531
	14	22	22	1.2578	0.7031	11	18	25	1.4297	7.5781
	17	19	28	1.3906	1.3281	27	17	20	1.3672	8.9063

low level	**1**	**1**	**1**	**0.5**	**0**	**1**	**1**	**1**	**0.5**	**0**
high level	**30**	**30**	**30**	**1.5**	**10**	**30**	**30**	**30**	**1.5**	**10**
decimals	**0**	**0**	**0**	**4**	**4**	**0**	**0**	**0**	**4**	**4**
factor name	**Spares**	**IQ**	**I Cap**	**Deg**	**ST**	**Spares**	**IQ**	**I Cap**	**Deg**	**ST**
	16	16	16	1	5	14	12	3	0.6094	8.6719
	23	17	19	1.0469	6.6406	28	20	21	1.1641	4.5313
	4	21	18	1.0391	9.0625	5	16	26	1.4063	4.6094
	17	8	30	1.2266	5.8594	20	3	28	1.0859	2.7344
	10	4	21	1.1328	5.625	15	5	25	1.0625	3.6719
	30	19	14	1.2656	8.9844	28	21	11	1.3984	2.3438
	10	18	10	1.4922	6.0156	6	26	15	1.1016	0.0781
	19	1	8	1.2109	8.4375	21	3	3	1.3438	2.8906
	13	10	4	1.4375	6.5625	5	6	5	1.1563	0.625
	29	29	23	1.2969	8.0469	20	16	29	1.3047	2.0313
	1	28	24	1.2344	8.8281	6	19	18	1.3828	2.6563
	29	2	16	1.2188	6.875	16	11	24	1.1875	2.8125
	3	1	23	1.1172	8.5938	12	6	26	1.3594	3.8281
	16	23	2	1.3203	5.9375	24	29	15	1.0938	1.7969
	8	24	3	1.1484	9.1406	5	18	12	1.4141	3.5156
	23	15	2	1.2734	5.3125	29	7	11	1.0313	2.2656
	7	8	1	1.4688	8.2813	13	5	6	1.3281	0.3125
	23	25	24	0.7578	9.6094	16	18	24	0.5391	2.5781
	2	20	22	0.7188	5.7813	6	28	27	0.9219	2.1875
	25	8	22	0.9766	7.8906	18	15	21	0.7109	4.7656
	11	2	19	0.75	8.75	3	6	26	0.625	2.5
	22	24	6	0.5469	5.0781	21	24	13	0.9922	0.4688
	12	22	11	0.5781	6.25	5	27	3	0.875	0.7813
	24	9	8	0.5234	6.7188	24	10	15	0.8281	0.2344
	9	12	2	0.5156	8.125	4	5	6	0.6875	0.1563
	22	23	17	0.8906	6.7969	25	27	20	0.8203	3.9063
	3	30	17	0.9297	8.5156	11	18	27	0.6484	4.2969
	23	9	22	0.5	9.4531	27	6	18	0.5547	0
	1	3	19	0.7969	8.3594	13	11	17	0.6641	2.9688
	22	17	8	0.9453	6.4063	18	20	4	0.8594	4.4531
	12	17	1	0.8047	5.1563	14	27	13	0.9844	3.0469
	17	9	9	0.7422	9.2969	20	13	6	0.5703	2.4219
						4	14	11	0.6328	1.0938

LIST OF REFERENCES

Anderson, B.E., Arostegui, M.A., and Lyle, D.L., “Methods for Conducting Military Operations Analysis,” Military Operations Research Society, Chapter 11, LMI Research Institute, McLean, Virginia, 2007.

Clockwork Solutions, Inc., “TLCM-AT Training Material,” Chapter 2, Naaman Gurvitz, 7 August 2007.

Clockwork Solutions, Inc., “Predictive Modeling Technology and Consulting Services in Support of Phase III TLCSM – Final Project Report,” (1992-2005), submitted to Headquarters, Marine Corps Installations and Logistics, 31 December 2007.

Clockwork Solutions, Inc., *Technical Reference Manual*, “Aircraft Total Life Cycle Assessment Software Tool (ATLAST),” Version 5.0., (1992-2005), Austin, Texas.

Marine Corps Order 4000.57, Enclosure (1), Subject: Marine Corps Life Cycle Management, 16 September 2005.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Commanding General, Training and Education Command
   MCCDC, Code C46
   Quantico, Virginia

4. Director, Marine Corps Research Center
   MCCDC, Code C40RC
   Quantico, Virginia

5. Marine Corps Tactical Systems Support Activity (Attn: Operations Officer)
   Camp Pendleton, California

6. Director, Operations Analysis Division
   Code C19, MCCDC
   Quantico, Virginia

7. Marine Corps Representative
   Naval Postgraduate School
   Monterey, California

8. MCCDC OAD Liaison to Operations Research Department
   Naval Postgraduate School
   Monterey, California

9. Director, Logistics Plans, Policies, and Strategic Mobility Division
   Code LX
   Navy Annex
   Washington, D.C.

10. Professor Thomas W. Lucas
    Naval Postgraduate School
    Monterey, California